

RR Lyrae Variables in the Halo of M33

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Abstract. The properties of RR Lyrae variables make them excellent probes of the formation and evolution of a stellar population. The mere presence of such stars necessitates an age greater than ~ 10 Gyr while their periods and amplitudes can be used to estimate the metal abundance of the cluster or galaxy in which they reside. These and other features of RR Lyraes have been used to study the Local Group late-type spiral galaxy M33. Though these studies are generally in their infancy, we have established that M33 does indeed harbor RR Lyraes in its halo and probably also in its disk suggesting that these two components formed early in the history of M33. The mean metallicity of the halo RR Lyraes is consistent with that of the halo globular clusters in M33 at $[Fe/H] \sim -1.3$. Little is known about the spatial distribution of the RR Lyraes; this will require wide-field time-series studies with sufficient photometric depth to allow both the identification of RR Lyraes and robust period determination.

1. Introduction

The class of pulsating stars known as RR Lyrae variables are located at the intersection of the instability strip and the horizontal branch in the Hertzsprung Russell Diagram. Their utility has been widely documented in the literature. As such, they can be referred to as the “swiss army knife” of astronomy.

Because of their low masses ($\sim 0.7 M_{\odot}$, Smith 1995), the mere presence of RR Lyrae stars in a stellar population suggests an old age ($\gtrsim 10$ Gyr) for the system. As such, one does not need to obtain deep photometry beyond the old main sequence turnoff in order to establish the presence of an old population. Generally speaking, *identifying* RR Lyrae stars does not require a substantial investment of telescope time.

The periods of the ab-type RR Lyrae stars are related to their metallicities. These variables pulsate in the fundamental mode and display a distinctive sawtooth appearance in their light curves. Using data on field RR Lyraes from Layden (2005, private communication), Sarajedini et al. (2006) found

$$[Fe/H] = -3.43 - 7.82 \log P_{ab}. \quad (1)$$

The dispersion in this relation (rms = 0.45 dex) is significant making the determination of individual stellar metallicities unreliable, but the relation is useful for estimating the mean abundance of a population of RR Lyraes. There is a more precise relation given by Alcock et al. (2000) that requires knowledge of the periods *and* amplitudes; with this relation, the error per star is reduced to ~ 0.31 dex and the precision of the resulting abundance distribution is narrower (Sarajedini et al. 2009).

Once the metallicities of the RR Lyraes are determined, their absolute magnitudes can be calculated. The published equations typically take the form of a linear relation between $[\text{Fe}/\text{H}]$ and $M_V(\text{RR})$. A number of different slopes and zeropoints have been derived for this equation, but there seems to be convergence on slope values of ~ 0.20 and zeropoints of ~ 0.90 (Chaboyer 1999, Gratton et al. 2003, 2004; Dotter et al. 2009).

The minimum light colors of ab-type RR Lyraes are largely independent of their other properties as shown by Guldenschuh et al. (2005) and Kunder et al. (2009). This is based on a concept originally developed by Sturch (1966). As a result, if the minimum light colors are well-determined, they can be compared with $(V - I)_{o,min} = 0.58 \pm 0.02$ and $(V - R)_{o,min} = 0.28 \pm 0.02^1$ in order to measure the line-of-sight reddening for each star.

As described above, RR Lyrae variables are powerful probes of the systems in which they reside - star clusters or among the field populations of galaxies. It is for this reason that studying them in the Local Group late-type spiral galaxy M33 provides valuable insights into the properties of this galaxy. Ultimately, we would like to know how ‘dwarf spirals’ like M33 fit into the process of galaxy formation in a Universe dominated by cold dark matter (CDM) with a cosmological constant Λ (Navarro, Frenk, & White 1997). Comprehensive knowledge of M33’s most ancient stars will shed light on this question. In the remainder of this contribution, we will describe how RR Lyrae stars have been used to this end.

2. Previous Studies

The history of RR Lyrae studies in M33 is relatively short. The earliest study is that of Pritchett (1988), who presented preliminary results for a handful of such stars. No data or light curves were shown, but Pritchett (1988) did estimate a distance of $(m-M)_0 = 24.45 \pm 0.2$ for M33 based on the RR Lyrae variables. This value is somewhat smaller than the average of several different determinations from Galletti et al. (2004) of $(m-M)_0 = 24.69 \pm 0.11$.

The first study to unequivocally identify and characterize RR Lyraes in M33 was that of Sarajedini et al. (2006). They used time-series observations of two fields in M33 taken with the Wide Field Channel of the Advanced Camera for Surveys (ACS/WFC) onboard the Hubble Space Telescope (HST). The observations consisted of 8 epochs in the F606W ($\sim V$) filter and 16 epochs in the F814W ($\sim I$) filter. The data were analyzed using the template-fitting software developed by Andrew Layden and described in Layden & Sarajedini (2000, see also Mancone & Sarajedini 2008). Based on these data, 64 ab-type RR Lyraes were identified. However, very few c-type variables were uncovered because of their generally lower amplitude.

The period distribution of the ab-type variables showed two peaks - one at longer periods which resembles the metal-poor RR Lyraes in M3 and M31 (Brown et al. 2004) and one at shorter periods which could be from metal-rich

¹Depending on how the minimum light color is measured, this value could also be $(V - I)_{o,min} = 0.27 \pm 0.02$. See Kunder et al. (2009) for details.

RR Lyraes in M33's disk. The presence of the latter population is somewhat uncertain given the recent work of Pritzl et al. (private communication). Sarajedini et al. (2006) found the mean metallicity of the metal-poor RR Lyraes to be consistent with that of halo globular clusters in M33 which have $\langle[\text{Fe}/\text{H}]\rangle = -1.27 \pm 0.11$ (Sarajedini et al. 2000).

Figure 12 of Sarajedini et al. (2006) shows that the M33 RR Lyraes are in their expected location in the color-magnitude diagram (CMD); in addition, their colors exhibit a dispersion that is consistent with being significantly affected by differential reddening. This suggests that some of the RR Lyraes are on the near side of M33 while others are in the disk or on the far side of the galaxy. One way to further investigate this possibility is to examine the distribution of RR Lyrae reddenings using the intrinsic minimum light color of the ab-types as mentioned in Sec. 1. This analysis was performed by Sarajedini et al. (2006) and shows that the RR Lyraes span the range from $E(V-I) < 0.1$ up to $E(V-I) \sim 0.7$. Given that the line-of-sight reddening to M33 is $E(V-I) \sim 0.1$, this suggests that RR Lyraes exist in the disk of M33 and in its halo (on the near and far side). We return to this point later as we discuss the most recent results on RR Lyraes in M33.

The primary result from the work of Sarajedini et al. (2006) was that M33 does indeed contain RR Lyrae variables in its halo. This suggests that the halo of M33 contains some fraction of stars with ages older than ~ 10 Gyr. In this regard, the halos of M33, M31, and the Milky Way are similar. It seems that they started forming stars at about the same time.

3. Latest Results

Building upon the work of Sarajedini et al. (2006), Yang et al. (2010) present an analysis of new HST/ACS/WFC imaging that is part of program GO-10190. The primary aim of this program is to study the star formation of the disk of M33 (Williams et al. 2009). As such, fields were obtained at four different disk locations roughly equally spaced along the major axis of M33. Figure 1 of San Roman et al. (2009) shows the locations of the disk fields. Here we report on the properties of the RR Lyraes in the second closest field to the center of the M33, which we designate DISK2.

The observations are composed of 16 epochs in the F606W filter and 22 in the F814W filter spanning a time window of ~ 3 days. Template-fitting analysis suggests the presence of 86 RR Lyraes in this field - 65 ab-type, 18 c-type, and 3 d-type variables. Figure 1 shows a montage of some of the light curves. The upper panel of Figure 2 shows the CMD of DISK2 along with the locations of the RR Lyraes. The middle panel of Fig. 2 displays the distribution in color of the ab-type RR Lyraes revealing the presence of two peaks - a primary peak at $(V-I) \sim 0.5$ and a secondary one at $(V-I) \sim 0.8$. We would like to know if this bimodality is due to reddening internal to M33. As such, we determine the reddening of each RR Lyrae using Sturch's method as described in Sec. 1 and then examine the distribution of reddenings to see if the fainter/redder RR Lyraes, those with $(V-I) > 0.74$, do indeed suffer from higher reddening. The lower panel of Fig. 2 illustrates this effect. The thin solid histogram represents all ab-type RR Lyraes while the dotted histogram shows only those with $(V-$

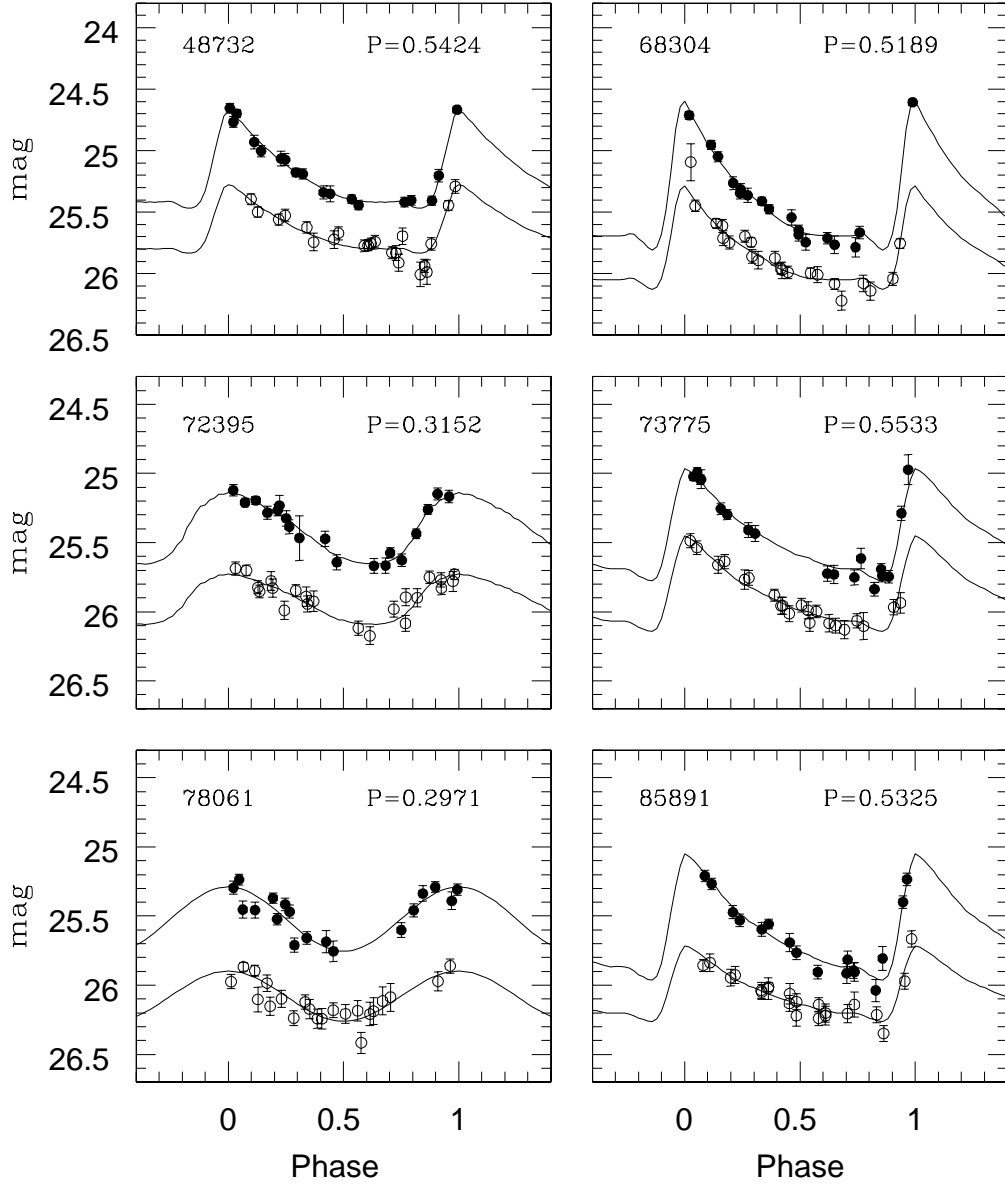


Figure 1. Each panel shows the phased light curve of an RR Lyrae variable in M33 from the study of Yang et al. (2010). The filled circles are the F814W points while the open circles are those measured in F606W. The solid lines are the best fit template to each star. The periods are indicated in each panel.

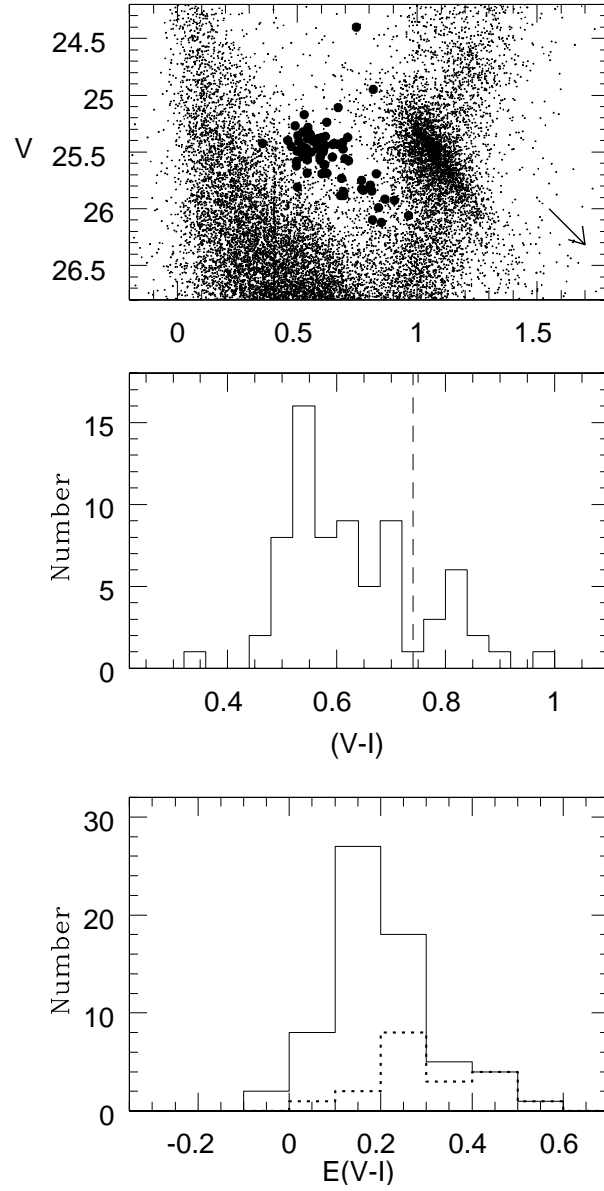


Figure 2. The upper panel shows the color magnitude diagram of the DISK2 field from the work of Yang et al. (2010) along with the RR Lyraes identified in this field (filled circles). The brightest two or three stars are likely to be anomalous cepheids. The arrow shows the reddening vector in the CMD. The middle panel illustrates the color histogram for the RR Lyrae variables, which appears to show a bimodal distribution with a primary peak at $(V-I) \sim 0.5$ and a secondary one at $(V-I) \sim 0.8$. The result of dividing the sample of ab-type RR Lyraes at $(V-I) = 0.74$ (dashed line) and plotting the distribution of reddenings (see text) is shown in the bottom panel. The thin solid line represents all ab-type RR Lyraes while the dotted line shows only those with $(V-I) > 0.74$.

$I) > 0.74$ (dashed line in the middle panel). Our hypothesis seems to be correct - that the fainter/redder RR Lyraes are being affected by extinction internal to M33. This suggests that the variables near $(V-I) \sim 0.5$ are on the near side of M33 while those with $(V-I) \sim 0.8$ are in the disk or on the far side.

We now seek to compare the properties of the low reddening and high reddening RR Lyraes. In particular, how do they compare in the Bailey Diagram? This is shown in the upper panel of Fig. 3 where we plot the periods and amplitudes of the DISK2 RR Lyraes (open circles - ab-types, open triangles - c-types; filled squares - d-types; filled circles - higher reddening ab-types). These are compared with the Oosterhoff I and II loci from Clement & Rowe (2000). We see that the ab-type RR Lyraes in M33 (both the low reddening and higher reddening samples) are consistent with those in Oosterhoff I Galactic globular clusters. The lower panel of Fig. 3 shows the period distribution of the RR Lyraes - the thin solid line represents all of these stars while the dotted line shows the higher reddening RR Lyraes. When compared to the period distribution of the low reddening variables, those with higher reddening exhibit no significant difference in their mean periods. This suggests that the mean metallicities of these samples are indistinguishable from each other. This reinforces the assertion that the low reddening RR Lyraes as well as most of those that suffer from higher reddening are likely to be in the halo of M33.

4. Conclusions

Studies of RR Lyrae variables in the late-type spiral galaxy M33 are still in their infancy but there are a few points we can make with relative certainty. First, M33 does indeed harbor RR Lyrae variables in its halo, which suggests that, similar to M31 and the Milky Way, there is an old component ($\gtrsim 10$ Gyr) to the halo of this galaxy. These variables have pulsational properties that are consistent with those in Oosterhoff I Galactic globular clusters. Furthermore, their mean metallicity is $[Fe/H] \sim -1.4$, which is consistent with the mean abundance of halo globular clusters in M33. Much more work is left to be done. For example, wide-field time-domain surveys of M33 will reveal the spatial distribution of the RR Lyraes. The capabilities of 30m telescopes will likely allow us to obtain kinematic and abundance information for RR Lyraes in M33. We can then study the detailed properties of the earliest epochs of star formation in a late type spiral galaxy. This has implications for how such galaxies fit into the Λ CDM paradigm for structure formation in the early universe.

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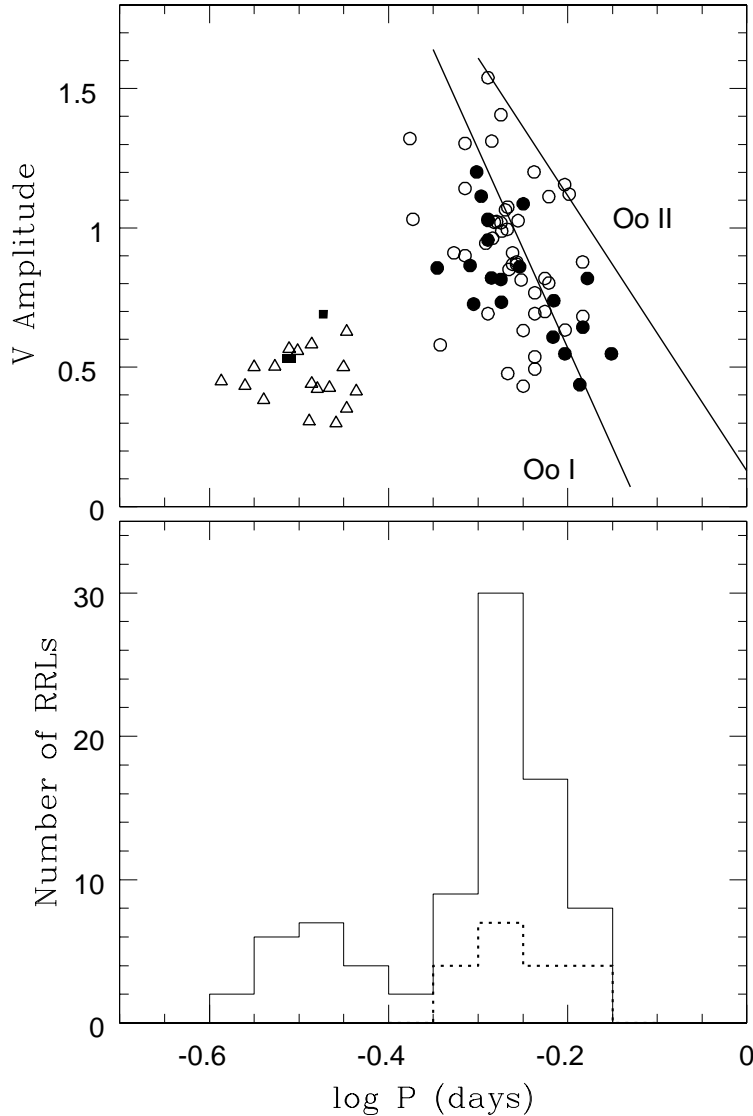


Figure 3. The upper panel is the Bailey Diagram for all RR Lyrae in the M33 DISK2 field. The open circles are the ab-type variables while the open triangles are the c-types. The few candidates d-type RR Lyrae are identified with filled squares. The solid lines are the locations of the Oosterhoff type I and Oosterhoff type II Galactic globular clusters from the work of Clement & Rowe (2000). The filled circles are the ab-type RR Lyrae with $(V-I) > 0.74$ from Fig. 2; these are likely to be located on the far side of M33's disk. The lower panel shows the period distribution of the RR Lyrae in the upper panel as the thin line while the distribution of RR Lyrae with $(V-I) > 0.74$ is designated by the thick dotted line. See text for a discussion of these histograms.

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